A METHOD FOR THE IDENTIFICATION AND ASSESSMENT OF CRITICAL TECHNOLOGIES NEEDED FOR AN ECONOMICALLY VIABLE HSCT

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Abstract

Researchers from the Aerospace Systems Design Laboratory (ASDL) at the School of Aerospace Engineering at Georgia Tech have been developing over the past three years a comprehensive methodology for the integration of aircraft design and manufacturing. NASA's High Speed Civil Transport (HSCT) concept has been selected as a pilot project for this study because of its potential global transportation payoffs and impact on U.S. world competitiveness. The proposed methodology is based on a Concurrent Engineering/ IPPD approach, and, in this case, is specifically applied to the design of an HSCT. The procedure employs the use of a Design of Experiments approach to facilitate the development of Response Surface Equations which capture the essence of sophisticated, computationally intense disciplinary analyses tools and replace them by simple second order polynomial equations. Since this aircraft has to be economically competitive to current subsonic transports, emphasis has been given throughout this study on understanding and assessing its economic viability. The determination of this objective is based on the required average yield per Revenue Passenger Mile ($/RPM), a metric that captures the concerns of all interested parties. The latest developments of ASDL's new methodology for the design of such affordable and reliable aircraft are outlined in this paper. However, the main objective of this paper is to describe the overall approach from concept formulation to concept feasibility and the identification and assessment of all possible means of achieving economic viability. Finally, different means of improving the economic viability of a hypothetical HSCT are examined, and their relative impact is quantified.

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Introduction

Over the past several years, the aerospace industry (airlines and manufacturers alike) has felt the impact of the combined effect of increasing aircraft systems costs and budget restrictions and is reacting through a series of initiatives to help minimize their overall system Life Cycle Costs (LCC)[1]. In fact, the need for a comprehensive method for the identification, assessment, and mitigation of critical technologies needed to ensure concept feasibility or its economic viability is apparent throughout the industry. It is also evident that new technology benefit studies must be accompanied by a corresponding risk assessment so as to avoid overly optimistic or pessimistic conclusions. Furthermore, the evolution of Multidisciplinary Design Optimization as a new discipline and the increased emphasis from government and industry to design for quality or affordability are enabling designers and decision makers to become aware of the benefits that could be achieved through an Integrated Product and Process Development (IPPD), Concurrent Engineering (CE) approach. Where IPPD brings together design and manufacturing considerations, while CE considers concurrently, as the word implies, contributions from the various pertinent disciplines.

In an attempt to encompass all these innovative ideas and develop a systematic, disciplined approach to aircraft design, a comprehensive methodology was developed by researchers at the Aerospace Systems Design Laboratory (ASDL) of Georgia Tech that considers concurrently all engineering disciplines and accounts for manufacturing concerns.

The High Speed Research initiative (which will eventually lead to the development of a High Speed Civil Transport (HSCT)[2]), undertaken by NASA and this country's industry provides a unique opportunity to develop and apply an Integrated Product and Process Design methodology for the identification of critical technologies needed to ensure the economic success of such a vehicle. This initiative is full of technological challenges affecting each and every one of the various disciplines involved (Aerodynamics, Structures, Propulsion, etc.)[3,4,5].

Designing such an aircraft from an affordability point of view implies an understanding of how the various discipline, design, and economic variables affect the feasibility and viability of this aircraft. Economic viability is usually measured through such metrics as total or direct operating cost per trip, aircraft acquisition cost, cash flow distribution, or required yield per Revenue Passenger Mile ($/RPM). If only one metric is to be tracked and optimized, then, for commercial transport studies, the required average yield per Revenue Passenger Mile is favored to be the Overall Evaluation Criterion (OEC)[3,5].

This paper presents the steps for the implementation of this IPPD methodology and focuses on means of improving the economic viability of this aircraft through relaxation of customer requirements, design constraints, or infusion of new technology. If the latter option is selected, the notion of risk to benefit rating is introduced along with such tools as the relevance trees and the technology/schedule risk ranking tables to assist the evaluator with the decision process.

Methodology Formulation

The Georgia Tech methodology can be described as a Concurrent Engineering approach to aircraft design applied in an Integrated Product and Process Development environment. Concurrent Engineering is commonly defined as a systematic approach to the integrated, concurrent design of products. Hence, this multi-disciplinary approach considers simultaneously all pertinent disciplines involved in a given design. If applied in the conceptual design phase it allows the designer to confront potential challenges and conflicting requirements in the early design stages when the system is still flexible enough to be altered[3]. Furthermore, the concurrent consideration of manufacturing and product development forms the foundation of an IPPD methodology. An approach like this might increase the initial costs and time needed for the early design stages, but produces significant cost savings in the long run and leads to a more efficient design. The IPPD environment envisioned by ASDL is depicted as Figure 1.

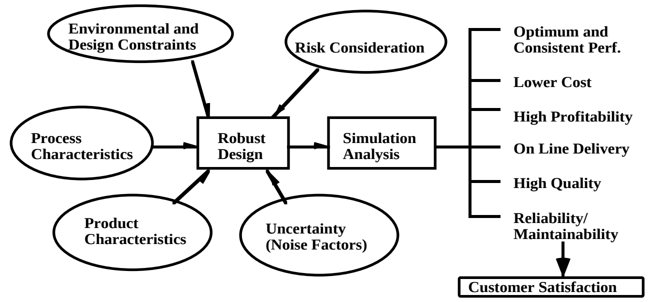

Figure 1: IPPD through Robust Design Simulation

In the traditional design process the designer employs a synthesis code to integrate information related to a similar type vehicle and to size the vehicle for a set of imposed design requirements and constraints. The design variables (product characteristics) are then varied within the pre-specified range of interest to yield an optimum configuration. In this case, optimization could be with respect to maximizing performance or minimizing empty or gross weight. The latter implying minimization of Life Cycle Cost of the aircraft.

On the other hand the proposed ASDL IPPD environment represents a more comprehensive approach to design and exhibits the following characteristics:

- It is based on a truly multidisciplinary synthesis tool, which can be tailored to the specific applications.
- Design variables are analyzed in an environment that considers or accounts for both product and process design variables.
- The analysis is subjected not only to design but also manufacturing and environmental constraints.
- It accounts not only for the benefits of new technologies but also for the risk associated with them. This way the effect and consideration of new technologies is modeled realistically, accounting for the penalty in increased RDT&E cost for the additional effort.
- It replaces the notion of "point design" for solutions that account for disciplinary, technological, economic, etc. variability. In a realistic representation some variables in the design process can not be set to a specific (optimized) value, because they are uncontrollable. These variables are commonly called "noise" factors[6], and cause a variability in the response dependent on their own distributions.
- In this new methodology designing for affordability does not mean any longer simple minimization of gross or empty weight. Instead it assesses and quantifies economic viability of an aircraft by modeling and accounting for manufacturer and airline business practices also.

- It links the economic viability assessment to the aircraft design via a synthesis code.
- Finally, the designer can examine and understand the design space around the optimum. This enables him to appraise how robust is the obtained solution.

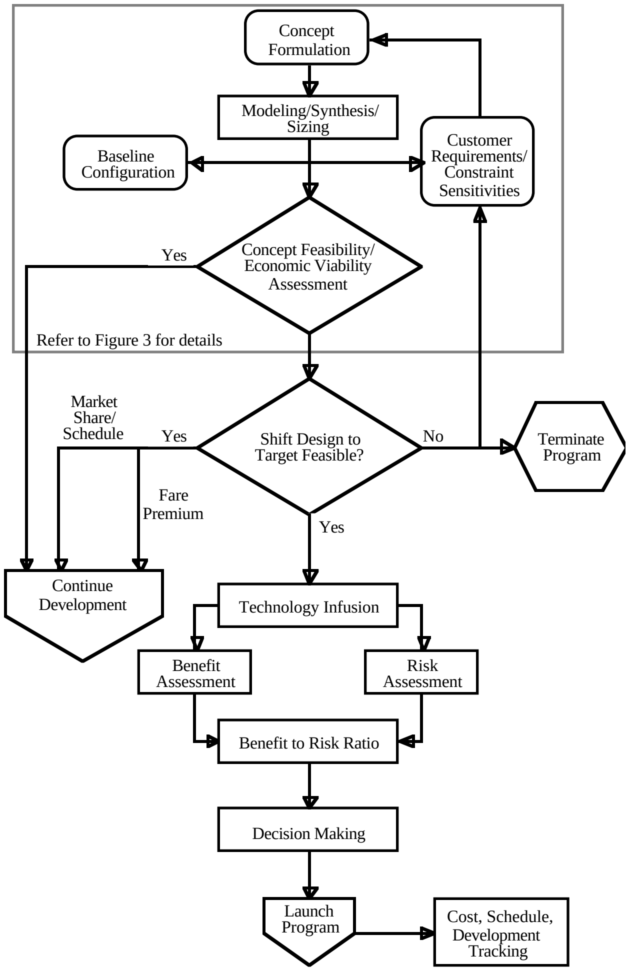

Figure 2: Critical Technology Assessment Methodology for Commercial Systems

The proposed methodology is attempting to achieve these objectives through the process illustrated in Figures 2 and 3. More specifically, the procedure is broken down to the following eight design phases or steps:

Step 1 : *Concept Formulation.* During this phase the design team is formed and the voice of the customer is translated into design and economic requirements through a series of brainstorming sessions. In addition, a mission profile is determined and all relevant design and environmental constraints are identified.

Step 2 : *Concept Modeling/Synthesis/Sizing.* Given the requirements and constraints from the previous step, a parametric study for each one of the disciplines involved is performed to create vehicle specific Response Surface Equations (RSE) for all needed responses. The outcomes of these analyses are then considered concurrently and integrated in a synthesis code to yield a sized vehicle. This vehicle is next referred to as the baseline for the economic viability evaluation (i.e. a vehicle that satisfies all requirements and is capable of flying the mission profile).

Step 3 : *Economic Viability Evaluation.* The baseline vehicle can now undergo an economic evaluation to determine whether the concept is economically viable. For commercial transports, viability may be measured in terms of the required average yield per Revenue Passenger Mile ($/RPM). The steps above are illustrated in the dashed box in Figure 2 and more explicitly in the expanded flowchart presented in Figure 3.

Step 4 : *Identification of means to improve the design's economic viability.* If the resulting feasible design is not economically viable, then viability may be achieved through customer requirement and/or design constraint alteration/relaxation, yield management, market share, technology infusion, or if everything else fails through a fare premium. It is also during this phase that the relative contribution of each one of the proposed alternatives to the response is quantified. These relative contributions are then used to assist the decision maker in the determination of a suitable course of action. (see Figure 3)

Step 5 : *Technology Benefit Assessment.* If technology infusion has been selected to enhance the economic viability, relative benefit gains associated with each alternative design improvement must then be assessed. Therefore, all possible new critical technologies must be identified and their effect on the evaluation criterion must be quantified. A relevance tree decomposition scheme may be utilized to assist this process.

Step 6 : *Technology Risk Assessment.* The technological/ schedule/ etc. risk associated with each of the design improvements proposed must next be examined. In order to measure or assess the risk, a readiness level and a corresponding confidence have to be determined for all alternative materials, processes, technologies, or methods. The readiness levels can be assigned to the various alternatives throughout the relevance trees so as to determine paths/options which may lead to reduction in risk.

Step 7 : *Evaluation, Decision Making, and Resource Allocation.* Each new critical technology is examined next from a combined risk to benefit viewpoint. This evaluation is subjected to funding/ budget and time constraints. Once the most appealing projects/ technologies are selected, the evaluator must verify that these projects can be completed by the scheduled date. Utilizing an activity network restrained by budget and schedule, the sequence of events/tasks that need to be performed can be determined. Because of constraints imposed by budget allocation and schedule deadlines this process will be iterative.

Step 8 : *Project/overall program tracking.* Provided that a critical technology development effort is going to be pursued, the program manager will have to conduct a series of periodic evaluations to determine if the program is on schedule. This process can be assisted through the identification of critical paths, show stoppers or potential problems ahead of time and carefully plan around them.

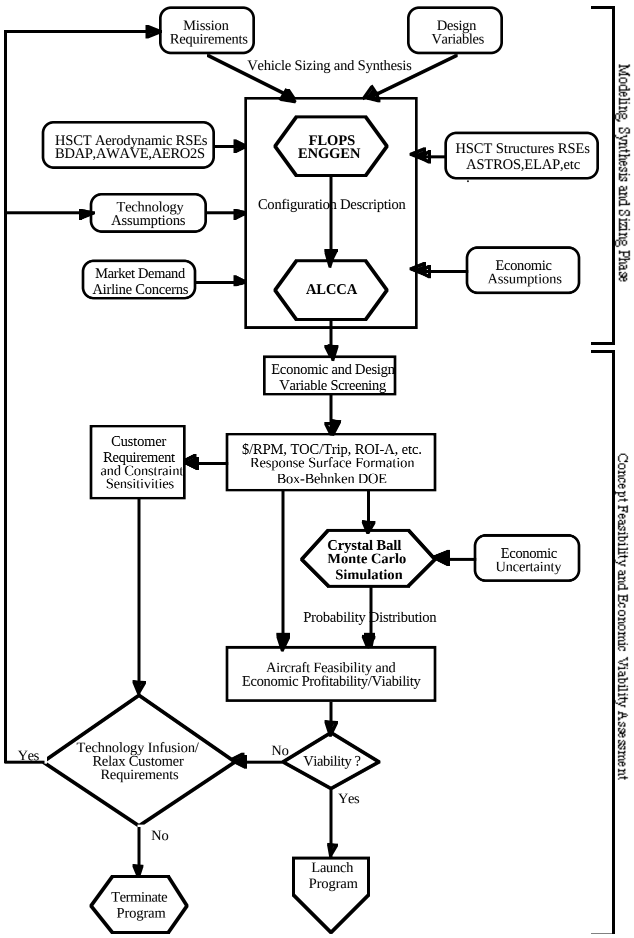

Figure 3: Feasibility and Economic Viability Assessment of a Given Concept

Methodology Implementation

Concept Formulation

During this phase of the proposed design procedure the voice of the customer is translated into a series of design (range, payload, speed, technology level, etc.) and economic (airline return on investment (ROI-A), desired load factor, target $/RPM, etc.) requirements. A mission profile is generated and all design and environmental constraints are identified (see Figures 2 and 3).

For the case study considered, the HSCT (see Figure 4) is envisioned to be an aircraft capable of flying supersonically (M = ~2.4) while carrying 300 passengers to destinations in excess of 5,000 nautical miles. Furthermore, stringent requirements have been placed on this aircraft to make it economically viable and affordable (required yield around 11 ¢/RPM, similar to current subsonic transport fares, e.g. B-777, A340, MD-11), as well as environmentally friendly by abiding to all appropriate FAA and EPA requirements. Such requirements include NO_X emissions in the order of 5 g/kg fuel during cruise flight, aircraft noise levels less than FAR stage III levels, and reduced community noise footprints. In fact, because of the inability, this far, to reduce the sonic boom to acceptable levels, it is almost a foregone conclusion that this aircraft will not be allowed to fly supersonically over land. This statement has far reaching implications for it not only forces the design to be compromised aerodynamically but it also penalizes its economic viability.

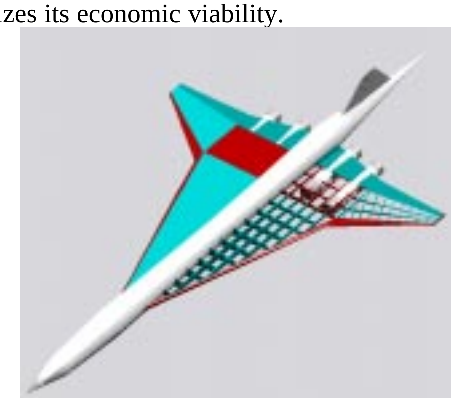

Figure 4: Georgia Tech's HSCT Double-Delta Baseline Configuration

Hypothetical HSCT baseline configurations for an all supersonic and a split subsonic/ supersonic mission (an arrow-wing and a double-delta wing concept respectively) have been generated based on all pertinent requirements and constraints. A representative mission profile for this HSCT comprised of a split sub-/ supersonic cruise performed at optimum altitude at Mach speeds of 0.9 and 2.4 respectively was generated and is depicted in Figure 5. The (horizontal) tail-less configuration, shown in Figure 4 is a representative example of one of the concepts presently studied at Georgia Tech.

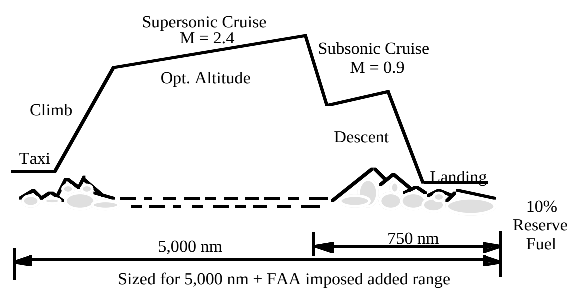

Figure 5: Representative HSCT Mission Profile

Concept Modeling/Synthesis/Sizing

Given the requirements and constraints provided from the previous step the various alternative concepts are first modeled by the available analytical tools at hand. The outcomes of these analyses are then synthesized to yield a sized vehicle (i.e. a vehicle that satisfies all requirements and constraints and is capable of flying the mission profile), while the sizing synthesis can be accomplished by such codes as FLOPS[7] (FLight OPtimization System) or ACSYNT[8] (AirCraft SYNThesis), which are the two most acknowledged public domain sizing programs.

At the conceptual design level, FLOPS and ACSYNT account for the effects of the various disciplines through a series of configuration specific data or empirically obtained equations. The structural component weight calculations, for instance, are based on a regression of available component weight data as a function of aircraft gross weight for a variety of different aircraft classes or types. The externally generated aerodynamics are represented in the form of drag polars at different segments of the mission (take-off, landing, cruise). The propulsion system cycle is usually defined prior to synthesis, with the engine performance on- and off-design points computed as a function of altitude, Mach #, throttle settings, etc. and provided in the form of look-up tables. Finally, stability and control is handled through the use of tail volume coefficients based on historical data.

At the preliminary design phase, the baseline configuration obtained from the procedure just described is handed off to the individual disciplines for further analysis. The more detailed analyses performed by these disciplinarians are then returned to the designer for incorporation into the design. This approach is time consuming, may lead to situations where the design is infeasible, and in general the control is taken away from the designer's hands.

Under the proposed CE/IPPD environment it may be hard to separate the conceptual and preliminary design phases from each other. In order to convert the synthesis code into a truly multidisciplinary preliminary synthesis tool, the method employs a Robust Design approach which is facilitated by statistical techniques such as the Response Surface Methodology (RSM). RSM is a set of techniques designed to gain a better understanding of the overall response of the system and to find the "best" value of a design response[9]. In most cases, the behavior of a measured or computed response is governed by certain laws which can be approximated by a deterministic relationship between the response and a set of design variables. Usually this relationship is either too complex or unknown, and an empirical approach is necessary. The strategy employed in such an approach is the basis of a response surface. In this study, a second order model in k-variables is assumed to exist. This model is chosen due to its precise accuracy in predicting the response. The second order polynomial for a response, R, is given by:

$$R = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum \sum_{i<j}^{k} b_{ij} x_i x_j$$

where,

b_i are regression coefficients for the first degree terms.
b_{ii} are coefficients for the pure quadratic terms.
b_{ij} are the coefficients for the cross-product terms.

The methodology developed is based on breaking down the various tasks of interest into their corresponding product and process characteristics, and then further decomposing the problem down to the individual disciplines. A two-level DoE is performed for each discipline to identify the most significant contributors using all pertinent design and manufacturing variables that should be considered. A linear regression experiment is set up next to obtain equations for each discipline metric (L/D, W_W, SFC, etc.) as a function of the most important design parameters (five to eight independent variables). These Response Surface Equations can then be substituted in the design synthesis code, and enhance it to become an HSCT specific true multi-disciplinary preliminary synthesis tool (see Figure 3). The problem is then recomposed back to the system level where optimization tradeoffs can be carried out, varying both the product and process design parameters. A point design optimization is then performed to arrive at an optimal system configuration.

Feasibility and Economic Viability Evaluation

The baseline vehicle can now be subjected to an economic evaluation to determine whether the concept is feasible and economically viable. As mentioned previously, the viability of commercial transport may be measured in terms of required yield per Revenue Passenger Mile. In order to optimize or simply determine the resulting $/RPM value for this vehicle a code accounting for manufacturing and airline business practices must be introduced and linked to the actual synthesis code. The authors have found that ALCCA[10,11], the Aircraft Life Cycle Cost Analysis program is the most suitable code to estimate the aircraft's economics. Hence, this code was linked to FLOPS by members of ASDL, and is now capable of simulating configurations that are optimized for the lowest $/RPM value.

As an illustration of this technique, an economic uncertainty analysis was performed to yield an analytical relationship between $/RPM and the various means which influence the economic viability of the HSCT. This economic study used the baseline configuration, depicted in Figure 4, to identify the economic uncertainty associated with this hypothetical HSCT. Twenty economic variables were identified, and a 2-level DoE was set up to perform a screening test. From this screening, the eight most significantly contributing variables were selected and subjected to a 5-level Central Composite Design (CCD)[9]. The remaining twelve variables which were not chosen for the RSE formulation were simply set to their most likely values. Figure 6 depicts the eight design variables selected (i.e. airline Return on Investment, load factor, economic range, fuel cost, aircraft annual utilization, manufacturer's learning curve, production quantity, and Engine Technology Factor) and categorizes them according to revenue, operations and support, and acquisition cost. The Engine Technology Factor is an adjustment factor (i.e. multiplier) for the engine CER which accounts for the uncertainty of the prediction capability for supersonic aircraft engines. These eight variables, however, cannot be directly controlled. Therefore, design equivalent variables must be identified that correspond to the chosen economic uncertainty variables. This way variability associated with economic uncertainty is implicitly controlled by minimizing its relative contribution.

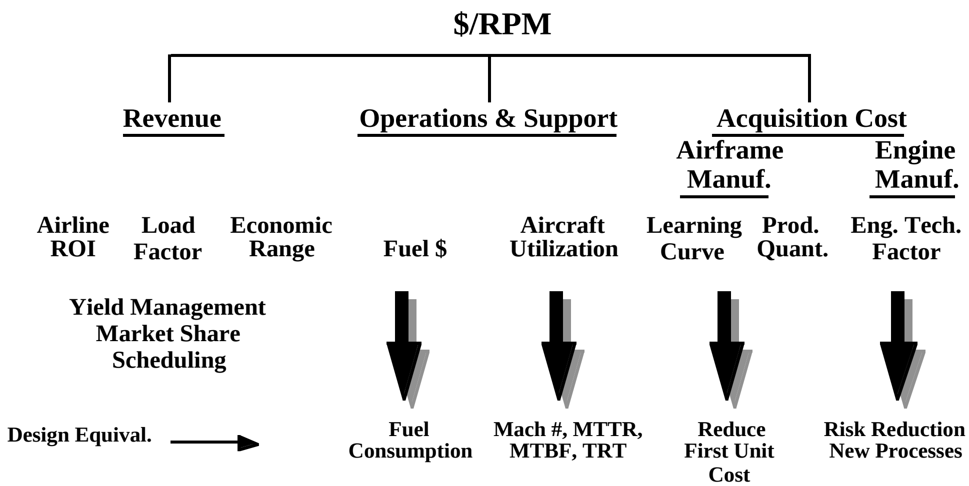

Figure 6: Identification of Most Significant Economic Contributors to the Economic Viability of an HSCT

Means of Improving Economic Viability

For each of the cases executed according to the CCD DoE scheme, a $/RPM value was computed and tabulated. Subsequently, an Analysis of Variance (ANOVA) was performed on these results to yield a mathematical expression for $/RPM in terms of the eight selected economic variables. However, this relationship can not be optimized, since none of the variables is controllable. In fact, these uncontrollable factors are referred to as "noise" variables which means that they can take any value within the selected range. If historical data are available for this class of aircraft, a probability distribution with a most likely point can be identified for each variable. For this study, all variables, except the Engine Technology Factor that was assumed to be uniformly distributed, were assigned to have a triangular distributions[5]. Utilizing these probability functions a Monte Carlo Simulation can now be employed to obtain the response probability distribution. The economic viability of this concept can be assessed next by comparing the economic target value, set by the average yield per Revenue Passenger Mile for the B-777, MD-11, or the A 340, against the statistics of this distribution (means, variance, etc.).

However, this investigation determined that the resulting $/RPM distribution corresponds to a feasible but not necessarily economically viable design (distribution is to the right of the target as seen in Figure 7). If this design provides indeed a non-viable economic solution, means must be identified to shift the distribution from the feasible but economically non-viable region into the feasible and economically viable region as displayed in Figure 7.

This can be accomplished by a combination of four means. In fact, viability can be achieved through the introduction of a fare premium to reflect the benefits associated with travel time reduction, yield management, market share/scheduling, or technology improvements which may simply be viewed as weight reduction. All four methods provide different means of improving the economic viability of an HSCT. However, it might be necessary to use a combination of these methods, if none of the methods by itself can improve the economic viability to a point where production can be initiated. Of all these choices the engineer can only control the design improvement aspects. Through the infusion of a new technology the designer can produce a system that is more fuel efficient, more reliable, more efficient from a producibility point of view, etc.

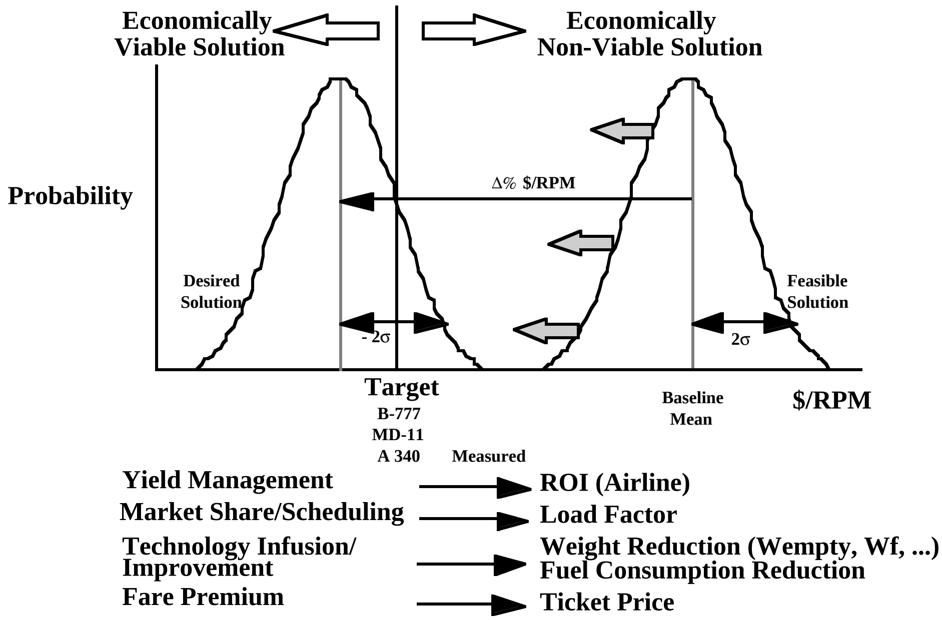

Figure 7: Possible Actions for the Transition of a Feasible Design Into the Economically Viable Solution Design Space - "Shifting the Target"

Figure 8 shows the effect of each means of improving the economic viability of an HSCT. The figure also quantifies the relative importance of technology benefits with respect to all other means which are outside the engineer's control. For this study it has been assumed that improvement through new technology is synonymous to a vehicle gross weight reduction. Therefore, for a 10% reduction in weight Figure 8 indicates that the $/RPM distribution will be shifted to target by 23%.

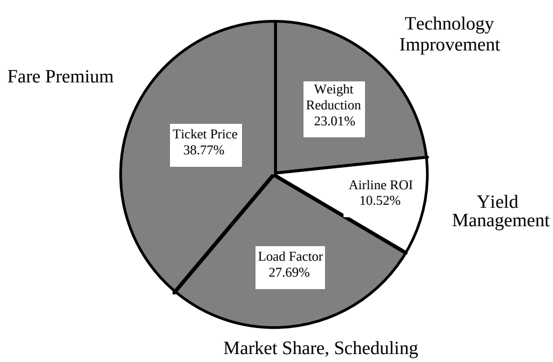

Figure 8: Means of Improving the Economic Viability of an HSCT

Referring back to Figure 7, the study also identified a required %-reduction in $/RPM in order to shift the probability distribution into the economically viable region. Figures 9 to 11 depict the effect that yield management, market share, and technology improvement have on shifting the mean to target for various fixed ticket surcharges. The line graph on these charts is read from the *right y-axis* as the % reduction in $/RPM that is required to produce an economically viable aircraft. As seen with the increase in fare premium, the % reduction in $/RPM is decreasing. This is due to the fact that the target value in Figure 7 is being shifted to the right. Therefore, the probability distribution does not have to be shifted as far to the left with the increased surcharge on the ticket fare. The bar charts depicted are with respect to the *left y-axis* values. For example, if a 10% fare premium was introduced, from Figure 11, it can be seen that for the aircraft to be economically viable, the weight of the aircraft would need to be decreased by 42% with respect to the baseline configuration. Assuming that the economic requirements can not be relaxed, the designer has to find a way of reducing the vehicle gross weight by 10-63% depending on the ticket fare premium.

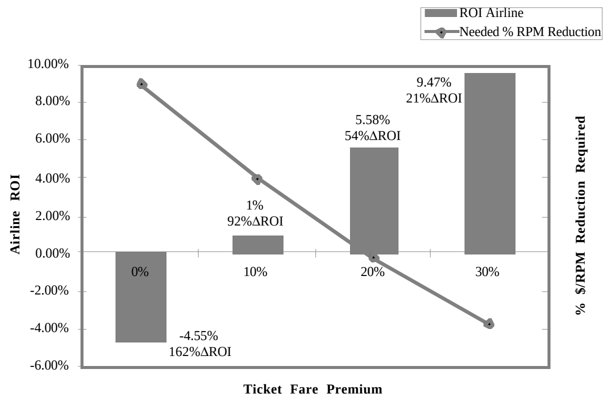

Figure 9: Yield Management Effect on Shifting Probability Distribution to Target

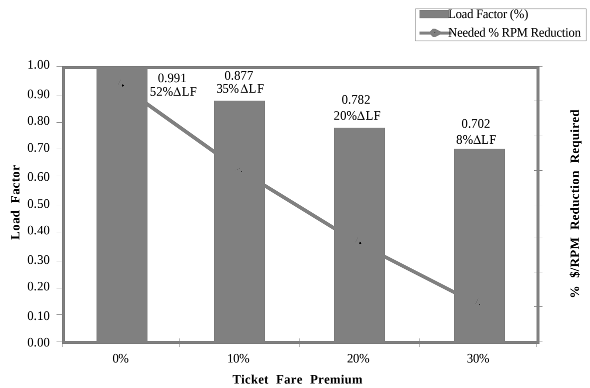

Figure 10: Market Share Effect on Shifting Probability Distribution to Target

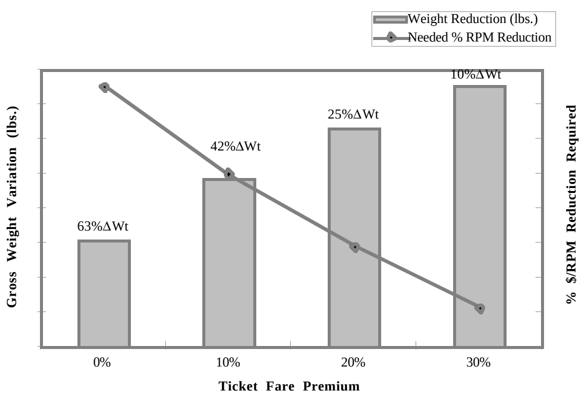

Figure 11: Technology Improvement Effect on Shifting Probability Distribution to Target

If new technologies must be identified, risk must also be assigned to each of these areas. Once the technologies and their associated risks have been identified, the entire scheme must be repeated hoping to yield an economically viable solution.

Technology Benefit Assessment

The study performed at the previous step helped quantify the need for new technologies and provided justification to such questions as:

Why is new technology needed?
Can project be achieved using current off the shelf technology ?

Questions that need to be addressed at this point include:

Is any technology critical to success of project?
- at what price ?
- what is the risk associated with it ?
- are there any alternatives ?
- what is the state of development ?
- can this technology be demonstrated/incorporated by date needed ?

In general, the need for technology infusion falls under either one of the following two categories:

A) Technology infusion associated with feasibility, performance criteria, violation of constraints.

This implies the introduction of a technological advance/breakthrough to satisfy design requirements. This in turn translates to an increase in developmental cost that has to be quantified. An increase in risk associated with this technology which may lead to schedule or cost overruns, and the possibility of program cancellation.

B) Technology infusion associated with economic viability.

If the baseline cannot achieve economic viability, new technologies may be introduced. This can imply a possible reduction in acquisition cost through advances in material usage or manufacturing process. Or a reduction in supportability or Life Cycle Cost through increased reliability. This of course will translate to added RDT&E expenses and possibly an increased acquisition cost.

For both categories the following questions have to be answered next:

i) Can existing technology lead to a successful product, measured by the selected overall evaluation metric?
ii) Can the program benefit from the infusion of "state-of-the- art" technology ?
iii) Are there any alternatives ? What are they ?
iv) Which one of these alternatives may benefit the program most without taking any unrealistic risk?

Since advances in technology are needed to make this program successful, all critical technologies that could benefit for the program must be identified before improvements can be made. This objective can be best achieved through a decomposition technique called the relevance or objective tree[12]. A relevance tree is a method which enables the totality of the contributing technologies of a complex product (that possesses a number of functions, systems, sub-systems, and components) to be explored in a systematic manner. This method can be used as both a forecasting and a planning tool. Such a tree illustrates that the fulfillment of the objective depends upon the accomplishment of substantial advances either from new technologies or significant progress in existing technologies. Relevance trees are used[12]:

- To establish whether a specified goal or objective is feasible.
- To identify alternative methods for satisfying the requirements at each level of the tree hierarchy.
- To decide performance objectives for each of the constituent parts.
- To focus attention on the need for radical new technological solutions if the overall objective is to be attained.
- To highlight where detailed forecasts for the constituent technologies are necessary when the achievement of a specified performance level within a given time scale is critical for success[12].

An example of a top level relevance tree is presented in Figure 12. It displays a relevance tree structure which was constructed for the overall objective of reduction in $/RPM. This overall objective can be decomposed into an economic objective, reduction in acquisition cost, and an equivalent design objective improvement through weight reduction. Ranges of possible values must be assigned to the design variables depicted in level 10, as seen in Figure 12. Within these ranges optimal settings have to be found that minimize the gross weight of the aircraft, which in turn minimizes the acquisition cost, which reduces the OEC, $/RPM. If no optimum can be found within the design ranges, areas where new technology infusion might occur must be identified, and the optimization analysis must be repeated.

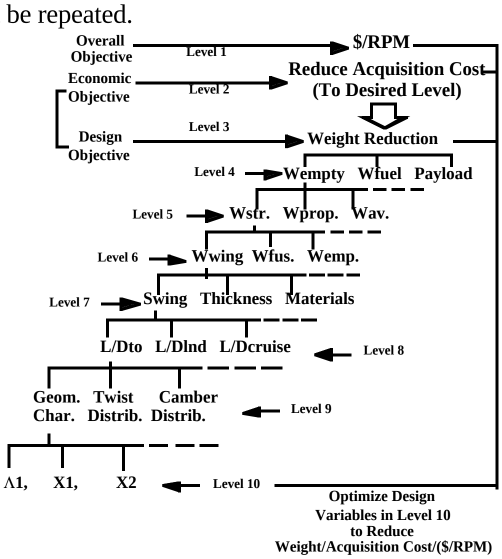

Figure 12: Acquisition Cost Relevance Tree

For instance, Laminar Flow Control (LFC) is one technique that can be used to increase the L/D ratio of the aircraft during the supersonic cruise segment to provide better aerodynamic characteristics. The proposed methodology would evaluate the values of the level 10 design variables for this technology that yield the optimum evaluation criterion. If the LFC cannot provide a viable solution by itself, benefits from other technologies infusions must be considered, The process is then repeated until a satisfactory solution is found. If none of the proposed options works, the decision maker might consider terminating the project before more money is spend on it. If on the other hand, one or a combination of new technologies are viewed as prime candidates for incorporation due to their benefit contributions, a risk analysis has to be performed to determine the risk penalty associated with it. If the risk and corresponding RDT&E cost are acceptable, the program can be launched. In general, the decision on use of a new critical technology will always depend on such considerations as:

• Technology - The project's scope definition is influenced by the technologies currently available. Throughout a project life cycle (especially long-term projects), emerging technologies may alter the project's scope.

• Funding - If a cost ceiling is established for the project, it may limit the project team's alternatives for meeting the customer's requirements.

• Resources - Limitations or availability of resources (e.g., people, tools, materials) can influence how the project team defines a project's scope, and may restrict their ability to meet programmatic objectives.

Technology Risk Assessment

Traditionally, risk is encountered every time there is a technological advancement or an engineering development. Risk may also be associated with scheduling, reliability, producibility, or cost estimating uncertainty. The Risk Assessment methodology proposed in this paper separates risk into two categories, risk through cost estimating uncertainty and schedule/ technological risk. Although in this paper the cost estimating risk is assumed to be independent of schedule/technical risk, the cost prediction does remain dependent on the schedule and technical assumptions.

According to this approach, the evaluation starts by determining whether the alternative materials/processes/ technologies/methods are ready for implementation. This is accomplished by identifying readiness levels and their corresponding confidence so as to provide a means of measuring/ assessing risk. The readiness levels can be assigned to the various alternatives throughout the relevance trees so as to determine paths or options which may lead to reduced risk.

The risk analysis assessment performed on any project or technology evaluated is comprised of three distinct phases: risk identification, risk determination, and risk control or mitigation. These stages of risk management are defined as follows:

- Risk Identification - The risk identification is the process of determining which risks are most likely to affect the project. This process relies on historical information, formalized risk checklists (Table I), and the collective knowledge and experience of the project personnel. Schedule/Technical risk is defined as the risk associated with evolving a new design to provide a greater level of performance or the same level of performance with the consideration of some new constraints, within a designated schedule.

Table I may be viewed as a standardized risk identification chart. It contains six different technology/schedule categories which may be encountered and assigns ten readiness or risk levels for each of the different categories, such as technology advancement, engineering development, reliability, producibility, alternate item, and schedule. Schedule and the various technical risk categories are treated together because they are interrelated and it is often very difficult to separate them. Sources contributing to schedule/technical risk are testing requirements, integration considerations, requirement changes, schedule aggressiveness, technological maturity, and system complexities. Similarly, the risk in cost estimation translates to the confidence of accurately predicting the cost of the project. Table II lists these categories.

Table I: Technology/Schedule Risk Categories and Scores [Ref. 12]

Categories	Risk			0=Low, 5=Med.,	10=High
	0	1-2	3-5	6-8	9-10
Technology Advancements	Completed (State of the art)	Minimum advancement required	Modest advancement required	Significant advancement required	New technology
Engineering Development	Completed (Fully tested)	Prototype	HW/SW development	Detailed design	Concept defined
Reliability	Historically high for same item	Historically high on similar items	Known modest problems	Known serious problems	Uncertain
Producibility	Production & yield shown on same item	Production & yield shown on similar items	Production & yield feasible	Production feasible & serious yield problems	No known production experience
Alternate Item	Exists or availability of other items not important	Exists or availability of other items somewhat important	Potential alternative under development	Potential alternative in design	Alternative does not exist & is required
Schedule	Easily achievable	Achievable	Somewhat challenging	Challenging	Very challenging

Table II: Cost Estimation Uncertainty Scores

	0 - Extremely Confident	1 - Very Confident	2 - Confident	3 - Fairly Confident	4 - Slightly Confident
Cost	Historically known for same item Off-the-shelf item Well defined price	Prediction Extrapolation Historically estimated for similar items	Estimated based on proven method Scope/definition of system is adequate Data are within CER Ranges	Estimated based on unproved method but certain assumptions Data outside CER limits	Major uncertainties exist Analyst unfamiliar with the cost model Estimating data sources not documented

Cost estimating risk is defined as uncertainty in a cost estimate due to limitations of the methodology employed. Some examples of uncertainty sources are: historical data (i.e., normalization or applicability of data), scope of program definition, degree of applicability and standard error of available CERs, extrapolation from data, and differences in "expert opinion." The cost estimating distribution is additionally based on uncertainty associated with any input parameter that was used to develop the point estimate. These can include: first unit costs, learning curves, cost-to-cost factors, complexity factors, etc.

• Risk Determination - Risk determination is the process of quantifying and evaluating the probability of risk occurrence and risk impact. In fact, risk is usually quantified in terms of potential cost or schedule impacts. Methods for performing risk assessments include:

i) traditional approaches that assign risks based on the experience of similar projects
ii) Monte-Carlo simulation techniques, which predict a possible range of outcomes for the project
iii) analytical methods that use mathematical probability to assess and combine the effects of individual risk events into an overall measure of risk, and
iv) a discrete event approach that uses decision trees, and influence diagrams to analyze risk.

In this study the risk determination is achieved by directly assigning confidence levels to projects/ technologies depending on their readiness or risk. Table III lists ten readiness descriptions and their corresponding risk level, readiness level, and confidence. According to this chart, risk is a probability distribution which reflects confidence. Each risk or readiness (the two are complimentary to each other) category maps to a specific point on this probability distribution. These confidence values are typical but by no means unique. In fact, they will vary from organization to organization and are dependent on such things as program starting date, budget restrictions, etc.

Table III: Technology Readiness and Confidence Levels

Risk Levels	Readiness Levels	Readiness Description	Confidence
0	9	Actual system flight proven on operational flight	100%
1	8	Actual system completed and flight qualified through test and demonstration	95%
2	7	System prototype demonstrated in flight	90%
3	6	System model or prototype demonstrated in a relevant environment	80%
4	5	Component validation in a relevant environment	65%
5	4	Component validation in laboratory environment	45%
6	3	Analytical and experimental proof of concept	30%
7	2	Technology concept formulated	12%
8	1	Basic principles observed and reported	5%
9	0	No concept formulation or only basic ideas	0%

• Risk Control - Risk control is the process for defining avoidance and/or mitigation procedures for minimizing downside risk. The primary approaches to risk control include:
i) <u>risk avoidance</u> that typically involves canceling a project or changing a technology
ii) <u>risk reduction</u> that involves identifying alternative approaches that with less loss potential or conducting a more sophisticated engineering analysis
iii) <u>risk transfer</u> that relocates risk to another party, (i.e., to another contractor who is better trained or equipped to handle a specific scope of work)
iv) <u>contingency funding</u> that establishes a budget to cover costs that may result from incomplete design, unforeseen and unpredictable conditions, or uncertainties.

Risk control in the proposed methodology is achieved through the inception of the risk-to-benefit-ratio. The concept as depicted in Figure 12 is relatively simple. A risky endeavor is to be undertaken if and only if, adequate product improvement (benefit) is associated with it. Inspection of Figure 12 indicates that for marginal benefit improvements the decision maker does not have much incentive to take risk. On the other hand, technological breakthroughs that can offer a significant improvement (i.e. greater 10%) are more appealing for risk taking. Obviously for an optimization case the lower the value of this ratio the better. In its limiting case where no risk is present the risk-to-benefit-ratio is equal to zero.

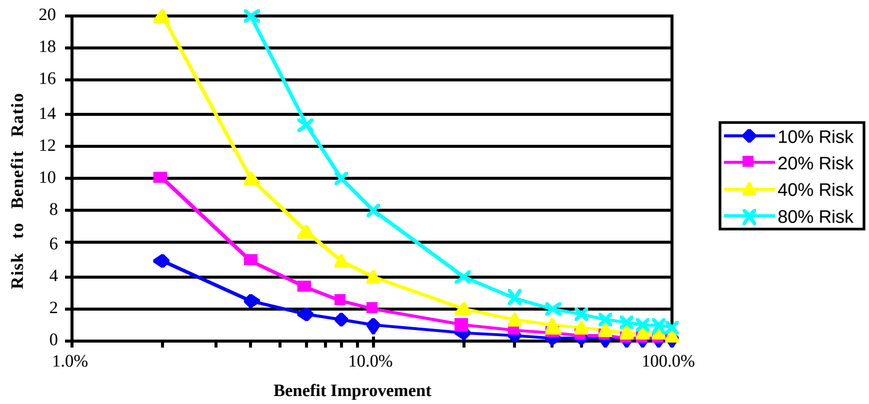

Figure 12: Risk to Benefit Ratio as a means of Risk Control

Decision Making and Resource Allocation

The various viable options must next be evaluated from a scheduling and/or a resource allocation view point. The decision making process may be assisted by a minimization of the risk-to-benefit-ratio between the various options. Benefit may also be adjusted to account for the increase in development cost. Projects or just technologies that exhibit the lowest risk-to-benefit-ratio may be given first priority over riskier alternatives yielding a higher benefit. Once the most appealing projects/technologies are selected, the evaluator must verify that these projects can be completed by the scheduled date. That can be achieved through an activity network diagram, which can easily illustrate and identify all bottlenecks and tasks that need to be performed either parallel or consecutively. Subsequently, a resource allocation must be carried out to identify if adequate manpower is available to complete all tasks within the allocated budget and schedule. Since this is a stochastic sequence of events, probability distributions for each step or path can be assigned or computed.

The following example illustrates how the decision making process can be altered once risk and budget constraints are taken into consideration. According to this hypothetical example (Figure 13) the $/RPM for an HSCT is to be optimized. It was determined that improvement could be achieved through either one of four different means: aerodynamics, propulsion, structures, and manufacturing. Furthermore, their relative importance or contribution to the response is identified. In this case any improvement associated with the propulsion system will yield the most benefit (50%). Each of the means depicted has one or more projects associated with it which could yield an improvement to the overall objective. The increase in yield from each action with respect to the baseline is listed in Table IV for each project. Each project is also associated with a specific uncertainty of achieving the targeted yield increase. This is expressed in the form of readiness for each project (see Table I). This readiness can be quantified once it is translated into confidence in that project using the probability distribution from Table III. Finally the last column lists the cost that is anticipated with each project.

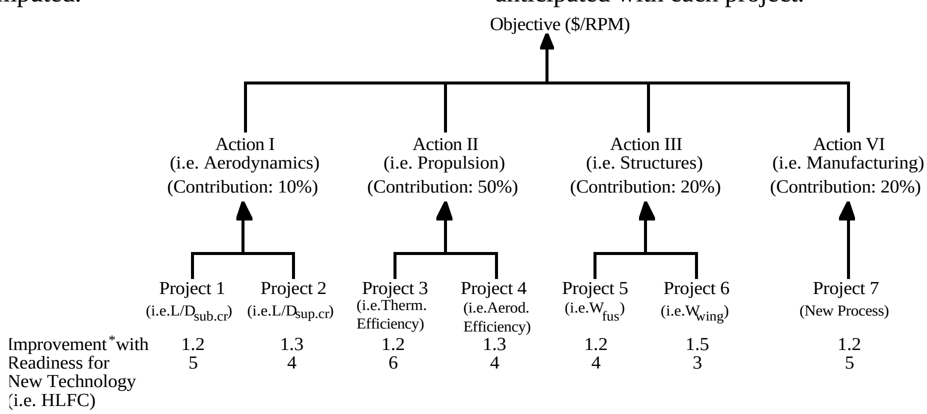

Figure 13: Hypothetical Relevance Tree Structure

Table IV: Projects to Increase Objective Yield

Project #	Benefit in μ	Readiness	Confidence	Cost in K$
1	1.2	5	65%	350
2	1.3	4	45%	550
3	1.2	6	80%	300
4	1.3	4	45%	600
5	1.2	4	45%	400
6	1.5	3	30%	800
7	1.2	5	65%	350

Table V: Resource Allocation Exercise for a List of Feasible Projects

Feasible Projects	Risk/Benefit	Objective Improvement	Actual Investment ($K)	Actual Worth of Investment ($K)	Normalized Worth of Investment ($K)
1-2	1.80	1.05	900	500.00	555.5
2-3	1.19	1.13	850	714.00	840.3
1-3-7	1.28	1.16	1000	781.20	701.2
1-4	1.82	1.17	950	522.00	549.4
3-4	1.50	1.25	900	600.00	666.6
4-5	2.03	1.19	1000	493.50	492.6
3-5	1.50	1.14	700	467.00	666.6
2-5	2.36	1.07	950	403.00	423.7
6	1.40	1.10	800	570.00	714.3
4-7	1.80	1.19	950	523.00	555.5
5-7	2.25	1.08	750	333.33	444.4
5-1	2.42	1.06	750	310.30	413.2

The example presented here has the purpose of illustrating the process of determining the Worth of Investment. Obviously, this value is highly dependent on the selection of projects, their readiness, and their associated cost, which have been chosen arbitrarily for demonstration purposes. The example is also meant to demonstrate that the project (or combination of projects) with the highest benefit (yield in objective) is not necessarily the most profitable one. The example has to satisfy a budget constraint of $1,000,000 and a required minimum benefit of 10% of the original objective outcome. Since there is not enough funding, according to the budget to fund all seven projects, the decision maker must decide which one(s) he or she ought to fund.

Every possible project combination which does not exceed the budget limit was examined. These feasible projects are presented in the first column of Table V. For each one of these projects the overall objective benefit, the associated risk, and the risk-to-benefit-ratio was estimated.

Inspection of Table V indicates that if risk taking was not a consideration, projects 3-4 should be funded, since they provide a 25% improvement. Once risk is considered, the decision maker may bypass that option and select option 2-3 for it provides reasonable improvement (13%) at a reduced risk-to-benefit-ratio of 1.19 versus 1.50.

During the resource allocation phase of the development the effect of risk may be included in the decision making process through what will be referred to here as Worth of Investment. Worth of Investment combines the effect of the risk-to-benefit-ratio with the budget spent on the project. Hence the objective is to minimize the risk-to-benefit-ratio or maximize the Worth of Investment which is defined as investment divided by the risk-to-benefit-ratio. By evaluating and comparing the actual Worth of Investment for all projects or their combinations, the optimal project (combination) with the highest actual Worth of Investment value can be determined. Table V also includes the figures for the actual Worth of Investment and the normalized Worth of Investment, which is defined as the actual Worth normalized by the total budget. Review of this column indicates that projects 2-3 has a normalized Worth of Investment of $ 840.3 K versus $ 666.6 K for projects 3-4. A simple way of interpreting these figures may be to consider that if risk was not present a $ 1 M investment will have the same buying power. On the other hand, with the presence of risk the investment made is worth less, because resources will have to be allocated to mitigate risk.

Project/Overall Program Tracking

Provided that a critical technology development effort is going to be pursued, the program manager will have to conduct a series of periodic evaluations to determine if the program is on schedule (see Figure 14). In order to avoid delays and cost overruns the program will have to undergo evaluation at constant intervals and remedies will have to be proposed if that happens. This process can be assisted through the identification of critical paths, show stoppers or potential problems ahead of time and carefully plan around them. Keeping in mind that when a program execution is compressed in time, risk increases significantly with more manpower required to get back to schedule and no room for further delays.

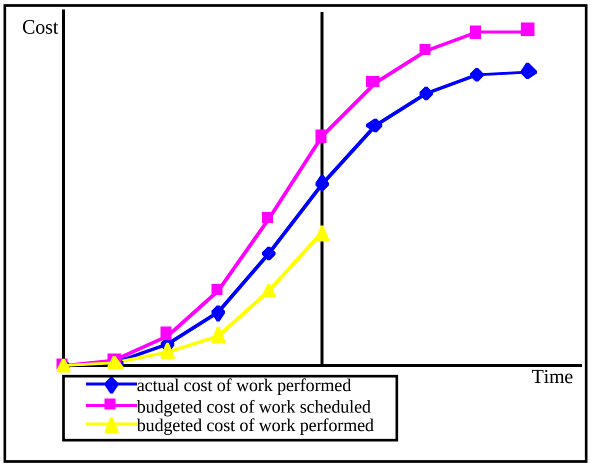

Figure 14: Program Cost/Schedule Tracking

Conclusions

A robust aircraft design simulation methodology has been developed and has been outlined in this paper. The methodology employs Concurrent Engineering practices, MDO advances, and is set up within an IPPD framework. Furthermore, it focuses on design for affordability and the means of achieving economic viability. This procedure has been applied on a hypothetical High Speed Civil Transport configuration, which satisfied all imposed design and environmental constraints. The authors came to the conclusion after the economic viability study was performed, that this concept can benefit greatly from the infusion of new technologies. Given this incentive, a means for the identification and evaluation of new technologies from both a benefit and risk point of view has been proposed. Finally, the procedure on how to assess and select the most suitable technologies was illustrated through an example.

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References

[1] Kusiak, A., *"Concurrent Engineering"*, John Wiley & Sons, Inc., 1993.
[2] Henderson, M., HSCT Project Manager, The Boeing Commercial Aircraft Group, *High Speed Civil Transport Program Review*, Seattle, WA.
[3] Mavris, D., Brewer, J., and Schrage, D., *Economic Risk Analysis for a High Speed Civil Transport*, Presented at the 16th Annual Conference of the International Society of Parametric Analysts, Boston, MA, May 1994.
[4] *High Speed Civil Transport Study*, Boeing Commercial Airplanes, New Airplanes Development, NASA CR4233, 1989.
[5] Mavris, D., Bandte, O., and Schrage, D., *Economic Uncertainty Assessment of an HSCT Using a Combined Design of Experiments/Monte Carlo Simulation Approach*, Presented at the 17th Annual Conference of the International Society of Parametric Analysts, San Diego, CA, June, 1995.
[6] Roy, R., *Taguchi Method*, Van Nostrand Reinhold, New York, NY, 1990
[7] McCullers, L.A., *Flight Optimization System*, User's Guide, Version 5.41, NASA Langley Research Center, December 1993.
[8] ACSYNT, Aircraft Synthesis Program, User's Guide, Version 3.0, NASA Ames Research Center, January, 1995
[9] Box, G.E.P., Draper, N.R., *Empirical Model-Building and Response Surfaces*, John Wiley & Sons, Inc., New York, NY, 1987.
[10] Galloway, T.L., and Mavris, D.N., *Aircraft Life Cycle Cost Analysis (ALCCA) Program*, NASA Ames Research Center, September 1993.
[11] Bobick, J.C., Braun, R.L., and Denny, R.E., "Documentation of the Analysis of the Benefits and Costs of Aeronautical Research and Technology Models". Technical Report submitted by SRI International to NASA Ames Research Center, Contract No. NAS2-10026, July 1979.
[12] Twiss, B.C., *Forecasting for Technologists and Engineers*, Peter Peregrinus Ltd., London, United Kingdom, 1992.
[13] Hoy, K.L. and Hudak, D.G., *Advances in Quantifying Schedule/Technical Risk*, The Analytical Sciences Corporation, The 28th DoD Cost Analysis Symposium, Xerox Document University, Leesburg, VA.